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CONDENSED SUMMARY REPORT
PRELIMINARY DESIGN STUDY OF
A LUNAR GRAVITY SIMULATOR

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FOREWORD

This report summarizes the preliminary design study of a Lunar Gravity Simulator system conducted for the NASA Marshall Space Flight Center, Advanced Systems Office, by the Lockheed Missiles & Space Company's Huntsville Research & Engineering Center (LMSC/HREC). The study was conducted under Contract NAS8-20351 during the period 15 June 1966 through 14 October 1966 by the HREC Systems Engineering Organization, Mr. R. S. Paulnock, Manager. Project Engineer for the program was Mr. R. B. Wysor. NASA technical direction was provided by Mr. Herbert Schaefer, R-AS-AT (Principal COR), and Mr. Robert R. Belew, R-P & VE-AA (Alternate COR).

SUMMARY

A preliminary design study was conducted of a Lunar Gravity Simulator (LGS) system for evaluating Lunar Surface Vehicles (LSV's). The four-month study investigated two- and three-dimensional LGS configurations. The two-dimensional (2-D) configuration restricted LSV longitudinal axis motion to the X-Z plane while the vehicle traverses a simulated lunar terrain. The three-dimensional (3-D) configuration allowed additional LSV yaw and lateral degrees of freedom. As a result of this study, 2-D and 3-D LGS system configurations were developed which utilize currently available servo control and drive system components. Dynamic errors of the LGS system were evaluated with an analog computer by developing mathematical models of the LGS/LSV system and conducting simulated obstacle negotiation at maximum vehicle velocity and variable obstacle heights. Results indicate that the lunar gravity error may be minimized by maintaining suspension cable lengths in a 30 to 53 foot range. Cost and schedule data were developed for the design, manufacture, assembly and checkout of the functional elements (excluding building facility, etc.) of the 2-D or 3-D system. The 3-D configuration was favored over the 2-D configuration because of simulation superiority and is recommended for further design and development efforts.

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1.0 INTRODUCTION

Plans for the exploration of the lunar surface are considering the development of Lunar Surface Vehicles (LSV's). These vehicles, such as the Local Scientific Survey Module (LSSM), would be used for transporting the astronaut and selected scientific instruments on exploratory lunar surface missions. The combination of rugged terrain, $1/6$ earth g environment and the desired surface speeds for the limited life support system creates problem areas not usually associated with surface vehicle mobility systems. These problems indicate that serious consideration should be given to a Lunar Gravity Simulator for evaluating full-scale Lunar Surface Vehicles as they traverse simulated lunar terrain in an earth gravity environment. This simulator system would be used to substantiate the LSV mobility system performance parameters, establish proven criteria for mobility system design, ascertain the man-machine relationships in the $1/6$ - g environment and train astronauts to operate LSV's in a $1/6$ - g environment.

With these objectives in mind, LMSC/HREC conducted a preliminary design study of a Lunar Gravity Simulator system under contract to the Marshall Space Flight Center. Primary tasks for the program were to conduct a preliminary design study of a two-dimensional (2-D)* Lunar Gravity Simulator system and to analyze the requirements and prepare conceptual designs of a 3-D system. (See References 1, 2 and 3.) Other tasks included investigating a system for suspending the LSV driver to simulate the $1/6$ - g environment and determining the costs and schedules for the design, fabrication, assembly and checkout of a Lunar Gravity Simulator system.

In this study, Lockheed used the most up-to-date information that was available, including earlier studies outlined in Table 1, and applied that information to derive a workable solution to the problem of lunar gravity simulation. Although the solution may not necessarily be optimum, it is straightforward and workable from the standpoint of high performance and low cost. This document presents a condensed summary of the study report presented in Reference 4.

* A two-dimensional LGS restricts LSV motion to a vertical plane with freedom in the roll, pitch, vertical and longitudinal dimensions; a three-dimensional system allows additional freedom in the yaw and lateral directions.

2.0 APPROACH

Lockheed's approach to the preliminary design of a Lunar Gravity Simulator (LGS) was guided principally by specifications derived from the Scope of Work (Reference 5). These basic specifications were that the lunar gravity simulation device:

- will suspend the test vehicle so that it will operate on an essentially horizontal plane;
- must be capable of accommodating vehicles of a mass weighing 450 kg to 4500 kg (approximately 1000 lb to 10,000 lb) at speeds from 0 to ± 20 km/hr (± 18.25 ft/sec); and
- must permit test vehicle freedom of movement in two dimensions, fore and aft ($\pm X$ axis) and vertical ($\pm Z$ axis) for the 2-D case. Also, the test vehicle must have freedom of movement in the roll (ϕ) and pitch (θ) directions (up to $\pm 35^\circ$).

In addition, specifications were that:

- The 2-D configuration should be capable of being expanded to a 3-D system to allow freedom of movement along the lateral ($\pm Y$) axis.
- In order to provide adequate simulation of $1/6$ -g, the device must respond to vehicle motion with minimum lag.
- The elevation difference in the test course for the test vehicle shall be assumed to be 7 meters (23 ft).
- Vehicle accelerations will occur as two types:
 - (1) Long duration, relatively low acceleration motions due to vehicle traversing and braking actions.
 - (2) Transient, high acceleration perturbations introduced by a simulated lunar surface.

The expected ranges of those accelerations were:

<u>Transient</u>	Fore and Aft:	Accel:	0.8 g
	Fore and Aft:	Decel:	2.0
	Up:		2.0 - 4.0
	Down:		1.0
<u>Long Duration</u>	Fore and Aft:		0.1
	Vertical		0.05

The LGS design that resulted from these criteria is a system in which the LSV is supported by steel cables rigged from an overhead suspension platform. High performance servo-controlled hydraulic motors, which power the cable winches, maintain constant tension equivalent to $5/6$ of the vehicle weight in the cable. In the two-dimensional configuration, a trolley, traveling on an overhead rail structure, supports and guides the suspension platform. A servo-controlled hydraulic capstan drive provides the power for maintaining vertical alignment between the platform and the LSV. An optical sensor provides the relative displacement error for maintaining this alignment. The three-dimensional configuration requires a 100 foot (minimum) span bridge structure with additional trolleys and drive systems for lateral and yaw degrees of freedom. Also, a short track between the support structure and the suspension platform provides the high acceleration response characteristics in the direction of vehicle travel. The following paragraphs describe the 3-D configuration and the corresponding sub-systems which could be used for a 2-D configuration.

2.1 THREE-DIMENSIONAL CONFIGURATION

The evolution of the 3-D design concept shown in Figures 1 and 2 requires the identification of basic components or sub-systems which could be used in either the 2-D or 3-D configurations. The logical interface is the suspension platform trolley and drive system. The suspension platform shown in Figure 2 is a rigid structure, which includes up to six wheels and two chassis suspension systems, partially supporting the LSV through suspension cables and constant force-controlled winch systems. The suspension cables are routed through pulleys which may be located to match the LSV attachment points. Figure 3 illustrates the basic elements of a typical constant force-controlled winch system. In each case, the strain gage type sensing is located at the LSV attachment point in order to accurately simulate the lunar g environment under highly dynamic conditions. A special harness and frame attachment at the wheel hub permits the wheel to be freely moved without interfering with the suspension cable. Suspension force control can be easily adjusted at a control console located as shown in Figures 1 and 3.

Other major functional elements of the 3-D LGS system are the short track (ξ), yaw (ψ) bearing and lateral (Y) trolley structure, and the bridge (X) assembly (Figures 1 and 2). Each of these elements has a corresponding drive system which maintains exacting alignment of the suspension platform with the LSV. The interrelation of these elements is shown in Figure 4. Two optical sensors located on the suspension platform (Figure 2), which provide relative misalignment signals for controlling the major drive systems, are focused on the light sources located on the LSV. These signals are differentiated so that displacement and rate signals are fed to electro-mechanical resolvers located on the yaw bearing structure. Output from these resolvers are the control signals for each of the drive systems. DC electric motors, using silicon controlled rectifier (SCR) control units, provide power for the bridge assembly, lateral trolley and yaw drive systems. An electro-hydraulic servo actuator, having a maximum stroke capability of ± 2 feet, powers the short track system.

The operating principle of the optical tracking system is illustrated in Figure 5. Two photo-multiplier tubes are focused on light sources located on the LSV pitch axis to provide the necessary alignment error signals described previously. The sensing element is a four-quadrant photocathode which provides a voltage output proportional to the lighted image area. The photo-multiplier tubes are mounted on the suspension platform (Figure 2).

References 3 and 4 describe the 3-D configuration in detail.

2.2 TWO-DIMENSIONAL CONFIGURATION

The two-dimensional LGS configuration utilizes the same basic suspension platform design described for the 3-D configuration. The primary difference is that the platform trolley which interfaces with the short track rails in the 3-D configuration is guided by two parallel rail structures which extend for the full length of the test area. Overhead structures support these rails at approximately 25 foot intervals. The limited overhead structure required reduces the facility height by 12 feet when compared with the 3-D configuration.

The optical tracking system for the 2-D configuration requires only one photo-multiplier tube to sense the longitudinal alignment and a corresponding light source on the LSV. The resulting error signal controls a servo-hydraulic motor which drives two cable capstans to control the motion of the platform.

References 2 and 4 describe the 2-D configuration in more detail.

2.3 COST AND SCHEDULE DATA

The estimated costs and program schedule were determined for both the 2-D and 3-D LGS configurations. This data include only the functioning elements of the LGS system. The building structure, simulated terrain, accessory equipment and instrumentation for operating the facility are not included. The following outline summarizes the program cost and schedule for each configuration.

<u>Item</u>	<u>2-D LGS</u>	<u>3-D LGS</u>
Engineering and Fabrication Manhours	16,800	31,430
Material Cost	\$193,000	\$294,300
Total Program Cost (Including Fee)	\$449,900	\$732,500
Program Schedule (Design, Fabrication, Checkout)	50 weeks	57 weeks

A more detailed breakdown of the cost and schedule data is given in Reference 4.

3.0 ANALYSIS AND SIMULATION

Design analysis of the Lunar Gravity Simulator system was principally that required for the constant force system for the cable suspension and the trolley drive system for maintaining LSV suspension platform alignment. Mathematical relations were derived to represent the functional components and control system of each system. These equations were programmed on Lockheed's analog computers to simulate the LGS/LSV combination under varying conditions of LSV surface velocity, lunar terrain and LGS design parameters. Both the MOLAB and LSSM lunar surface vehicles were included in the analog simulation. The principal design parameter investigated was the suspension cable length and the effect of its variation on the lunar g simulation. The results of this investigation are discussed in the following paragraphs.

3.1 CONSTANT FORCE CONTROL

Simulation of lunar g in the earth g environment requires a constant force control on each of the LSV principal masses. The proposed method for accomplishing this in each of the suspension cables was described in the previous section. This technique was evaluated by an analog computer simulation of the vehicle and control system. The primary elements of the constant force control system was shown in Figure 3. This system requires an electronic compensation network because the uncompensated control system was found to have very poor damping characteristics (7% of critical), especially in the wheel suspension devices. A tandem type compensating network was found necessary to increase system damping to approximately 70% of critical. Conventional electronic hardware can be used for this network.

A ramp-type obstacle was used for the dynamic evaluation of the LGS/LSV system in the roll and pitch configurations. For the roll configuration, the simulation was analogous to a front and rear wheel simultaneously engaging the obstacle. In the pitch configuration, the simulation was analogous to both front wheels and both rear wheels sequentially engaging the obstacle. Typical output data for the pitch configuration simulation is shown in Figure 6, which illustrates the rear wheel dynamic characteristics resulting from both front wheels engaging a 1.0 foot ramp obstacle followed by both rear wheels engaging the same obstacle. The simulation is shown for the LSSM vehicle with a surface velocity of 9.0 km/hr (8.2 ft/sec) and an LGS suspension cable length of 50 feet. The rear wheel diameter is superimposed on the rear wheel displacement/time chart to illustrate the obstacle engagement and departure from ground contact. The rear wheel force error, proportional to lunar gravity error, is closely related to the vertical velocity as shown.

Figure 7 illustrates a comparison of the rear wheel dynamic characteristics in lunar gravity and with simulated gravity using the LGS. The corresponding lunar gravity error is also shown. These characteristics resulted from the same LGS/LSV conditions described for Figure 6.

One of the significant results of the LGS dynamic analysis with analog simulation was the effect of variable suspension cable length on lunar gravity error. Figure 8 illustrates the peak lunar gravity error versus cable length for the LSSM hitting a one-foot obstacle at 9.0 km/hr. As discussed previously, these peak errors were strongly influenced by the vertical velocity transients at the attachment points. The importance of minimum cable length to minimize the gravity error is indicated. The minimum cable length of 30 feet was established by the static errors caused by variations in LSV roll and pitch attitudes discussed in Reference 2. Adding the required elevation change of 23 feet (7m), the recommended cable length range was 30 to 53 feet, as indicated in Figure 8. Note that these simulation errors are shown for an extreme condition and would be considerably smaller for normal operating conditions.

The analog data results for both the LSSM and MOLAB vehicles were reviewed to establish a limit design criterion for the LGS. This resulted in the selection of a one-foot obstacle height with the vehicle engaging the obstacle at maximum velocity and a suspension cable length of 60 feet. This resulted in peak dynamic characteristics well over the ride comfort limits anticipated for the LSV. The corresponding lunar gravity errors may be as high as 20% (peak). Whether this level of error will actually be approached is doubtful because of the severe obstacle/velocity combination. Peak errors under normal operation should be less than 10%.

The force control systems evaluated were found to be more than adequate for the LGS requirements. Analysis and simulation of these systems are discussed in detail in References 2 and 4.

3.2 SUSPENSION PLATFORM DRIVE SYSTEM

The more critical drive system for maintaining vertical alignment between the suspension platform and the LSV was that required to drive the platform as the LSV is exposed to high fore- and aft-transient accelerations. This drive system, commonly termed the "trolley system" for the 2-D configuration and the "short track system" for the 3-D configuration, was controlled by the optical tracking system and the electrohydraulic actuators described previously in Section 2.1. Dynamic evaluation of the drive system was accomplished by an analog computer simulation which represented the LGS/LSV inertias, the control system and the suspension cable dynamics (lateral vibration). Deceleration step function pulses of varying levels were imposed on the LSV for a total velocity change of 4.4 km/hr (4 ft/sec). Tractive force errors were recorded for this dynamic condition and various suspension cable lengths. Peak errors for the most severe condition, the MOLAB vehicle at a maximum speed of 20 km/hr (18.25 ft/sec), is shown in Figure 9. These results indicated a peak tractive force error of less than 2.5% of the nominal LSV acceleration capability (0.1 g). This error was found to be a function of vehicle velocity. Thus, the LSSM vehicle, with a maximum velocity of 9.0 km/hr (8.2 ft/sec), indicates a dynamic tractive force error of less than half the MOLAB error. Results of the trolley drive system analog simulation indicated that the system response was more than adequate for the LGS requirements.

A detailed discussion of the drive system, including the additional drives for the 3-D configuration, may be found in References 2, 3 and 4.

4.0 FACILITY CONSIDERATIONS

4.1 REQUIREMENTS

One of the important considerations for the LGS was the facility requirements for the 2-D and 3-D configurations. An enclosed or sheltered facility was found desirable because normal weathering elements may interfere with planned tests or may erode the simulated terrain. Also, it was considered desirable to implement the LSV testing with special lighting to test the driver's perception to shadowed obstacles and the subsequent negotiation problems. The following outline summarizes the facility requirements for the 2-D and 3-D LGS configurations.

<u>Minimum Requirement</u>	<u>2-D LGS</u>	<u>3-D LGS</u>
Vertical height, feet	63	74
Width, feet	25	100
Length, feet	250	200
Volume, ft ³	400,000	1,500,000
Total support load	11,000 lb rolling + 40,000 lb crane rail	45,830 lb rolling
Electrical power	56 hp (75 kw)	281 hp (376 kw)

Dimensional data was determined from the minimum required to house the functional elements of the LGS and the terrain surface required for a minimum of mobility testing. For example, the 3-D LGS width and length were determined by the maximum anticipated vehicle turn radius. The electrical power requirements listed are the approximate total ac electrical power required for the drive-motors and the hydraulic pumps.

4.2 CANDIDATE FACILITIES

An isometric view of a facility for a 3-D LGS configuration with simulated lunar terrain is shown in Figure 10. Typical paths for evaluating the LSV mobility characteristics and driver performance are illustrated. A preliminary investigation indicated that sheltered facilities with these approximate dimensions and with adequate crane rail capacities are in existence at Marshall Space Flight Center. (See Reference 4.) Buildings at MSFC were candidates for a 2-D configuration also, but the 2-D LGS would not fully utilize the internal space available.

One existing facility that could possibly be modified is the Langley Lunar Landing Research Facility (LLRF) in Virginia, which was designed for research in piloting problems for a lunar approach and touchdown. The facility is designed to support a LEM with full-fuel load (30,000 pounds) but the present tests use a half-scale prototype weighing 10,000 pounds. The facility consists of an open gantry structure with an overhead crane. The crane offers several appealing characteristics. It has high speed (≈ 50 ft/sec) capability and is servo-controlled to enable the crane to follow the vehicle's linear motions and to keep the suspension cables essentially vertical. Nominal usable interior dimensions covered by the bridge crane are 175 feet high, 50 feet wide and 400 feet long. A comparison of the LGS requirements and the Langley LLRF is shown in Table 2. This comparison is based on the following modifications of the LLRF:

1. A suspension platform, with separate winch systems (Z-axis) for the LGS wheels and chassis, is installed on the LLRF bridge and dolly structure (2-D and 3-D LGS).
2. A short-stroke (± 2 ft) high-acceleration longitudinal track framework is required for both the 2-D and 3-D systems in addition to the existing drive system. This will provide the system with a ± 2.5 g transient acceleration capability.
3. A yaw bearing between the short track frame and the suspension platform is essential for the 3-D LGS. The yaw capability is not required for the 2-D system, but would greatly facilitate vehicle turnaround.
4. Alignment of the suspension platform with the LSV would be accomplished by the optical sensing system described in Section 2 of this report.

For the 3-D LGS, the LLRF does not quite meet all requirements. First, the lateral width is much less than desired. A test course using 45-degree turns rather than full 90-degree turns could be devised to conduct a somewhat limited test program. Second, the lateral velocity and acceleration capabilities are marginal even with LSV at 16.5 km/hr (15 ft/sec) on the 45-degree turns. Therefore, the LSV maximum velocity in the turns must be reduced to about 13.2 km/hr (12 ft/sec), and less-than-maximum deceleration rates would have to be observed. Third, the 175 ft bridge height would result in peak lunar gravity errors of as much as 100% (Figure 8), which would create doubt as to the validity of the resulting test data. The most optimistic reduction of height to 140 ft would still result in a 75% peak error.

With the exception of height and the corresponding cable length problem as discussed above, the LLRF meets the major requirements of the 2-D LGS configuration. This is noted by the plus features in the 2-D column of Table 2.

In summary, it appears that the LLRF offers only a high-speed bridge crane and crane structure which would require extensive modifications to be applicable to LSV testing.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The primary design study of the Lunar Gravity Simulator system resulted in two-dimensional (2-D) and three-dimensional (3-D) configurations which utilize the same basic suspension platform hardware for supporting five-sixths ($5/6$) of the weight of the lunar surface vehicle. Either configuration may be built from currently available components and hardware. The two configurations differ primarily in the mechanisms

for positioning the suspension platform. A more complex drive control system is required for the additional two-degrees-of-freedom (platform yaw and lateral translation) required for the 3-D system. Conversely, the 2-D system may require the addition of more primary structure in order to utilize existing facilities.

The 3-D LGS system is favored for further design and development efforts because it offers many more simulation advantages. However, facilities for the LGS should be extensively investigated and a selection made before further design efforts are begun. The facility study should include, but not be limited to:

1. Further examination of current and future LSV mobility system turn radius and speed capabilities to ensure that the size specifications of the facility are adequate.
2. Determination of facility availability.
3. Evaluation of suitability for LGS requirements with the 3-D system as a primary consideration and the 2-D system as secondary.
4. Determination of modifications necessary for installing the LGS (including the estimated cost and schedule).
5. Investigation of the potential for joint utilization with other similar programs (current and future).

After a suitable LGS facility is selected, the design, manufacture, assembly and checkout of a complete LGS system should be initiated. This is estimated to cost approximately \$450,000 for the functioning elements of the 2-D system and \$732,500 for the 3-D system functioning elements.

6.0 REFERENCES

1. "First Interim Report, Preliminary Design Study of a Lunar Gravity Simulator," LMSC/HREC A783082, 29 July 1966, Rev. A.
2. "Second Interim Report, Preliminary Design Study of a Lunar Gravity Simulator," LMSC/HREC A783245, 9 September 1966, Rev. A.
3. "Third Interim Report, Preliminary Design Study of a Lunar Gravity Simulator," LMSC/HREC A783335, 25 October 1966, Rev. A.
4. "Final Report, Preliminary Design Study of a Lunar Gravity Simulator," LMSC/HREC A783336, November 1966, Rev. A.
5. Scope of Work, Exhibit "A" of NASA/Marshall Space Flight Center Procurement Request No. DCN 1-5-21-00032, 26 October 1965.

Table 1
SUMMARY OF INFORMATION SOURCES FOR GRAVITY SIMULATORS

Source	Sponsor	Document	Essential Content	Related Technology useful to LGS Program
Northrop Space Laboratories	NASA-MSFC	NSL E 30-44 April 1965	Lunar Gravity Simulator for MTA Test Program	Established ground rules and design criteria; Reviewed facilities for use in program; Compared and chose a horizontal plane concept from several types; Support systems used for sensing position changes.
Northrop Space Laboratories	NASA-MSFC	NSL E 30-61 August 1965	Continued Design Study for a Limited Capability Simulator	Considered additional inclined plane concepts, but found horizontal plane concept best. Continued design using a limited capability system (no y-axis capability - straight line operation).
Northrop Space Laboratories	NASA-MSFC	NSL E 30-80 March 1966	Feasibility Study of Langley LRF for MTA Tests	Detailed study of rework needed to adopt Langley Lunar Landing Research Facility for MTA Tests. Detailed sequential test program for MTA.
Aircraft Armaments	NASA-MSC	ER-2938 January 1963	Conceptual Design of a Space Motion Simulator	Structural design and analysis; Instrumentation for sensing displacement, velocity, acceleration; Control system for main generator; Translation system selection criteria.
Aircraft Armaments	NASA-MSC	ER-3377 March 1964	Continued Study of a Space Motion Simulator	Inclusion in analysis of viscoelastic damping of main structure; Revision of drive motors recommendation to an ironless motor; Use of silicon controlled rectifiers for control; Detailed study of harness arrangements for astronauts.
Langley Research Center	NASA-Langley	NASA TND-2636 February 1965	Lunar Landing Simulator Tests of Mock-up LEM vehicles	Describes servo hydraulic motor driven winch and cable support system for simulating 1/6 g environment.
Langley Research Center	NASA-Langley	NASA-STAR X63-14590 July 1962	Langley Lunar Landing Research Facility	Describes facility dimensional and performance data.

Table 2
COMPARISON OF LGS REQUIREMENTS WITH LLRF CAPABILITY

	LGS Requirements	LLRF Capability	2-D LGS	3-D LGS
Height	74 ft	175 ft	-	-
Width	100 ft min. ②	50 ft	+	-
Length	200 ft min.	400 ft	+	+
Vertical (Z-Axis)	See Note ①			
Travel	23 ft	LLRF Modification required.	.	.
Velocity	①	See Note ①		
Acceleration	①			
Lateral (Y-Axis)				
Travel	100 ft min. ②	50 ft ③	N/A	-
Velocity	15 ft/sec ③	10 ft/sec	N/A	Marginal
Acceleration	± 0.2 g ③ ④	± 0.1 g	N/A	Marginal
Longitudinal (X-Axis)				
Travel	200 ft min. ⑤	400 ft	+	+
Velocity	18.25 ft/sec	49.7 ft/sec	+	+
Acceleration	± 0.2 g ④	± 0.17 g, -0.39 g	Marginal	Marginal

Notes:

- ① A suspension platform and associated suspension device are required to provide independent suspension for each wheel and chassis. See Table 2.3 for separate wheel and chassis requirements.
- ② The 2-D LGS requires only 25 ft width and no lateral travel.
- ③ The LLRF width imposes a vehicle turn angle limitation of about $\pm 45^\circ$ from the longitudinal axis. When this limitation is used, the 3-D LGS requirements are: velocity = 10.5 ft/sec and acceleration = ± 0.14 g.
- ④ This value is for the bridge drive systems only. A short track, or drive mounted with yaw capability, is required to meet transient (± 2.5 g) acceleration requirements.
- ⑤ 3-D LGS only. The 2-D system requires approximately 250 ft.

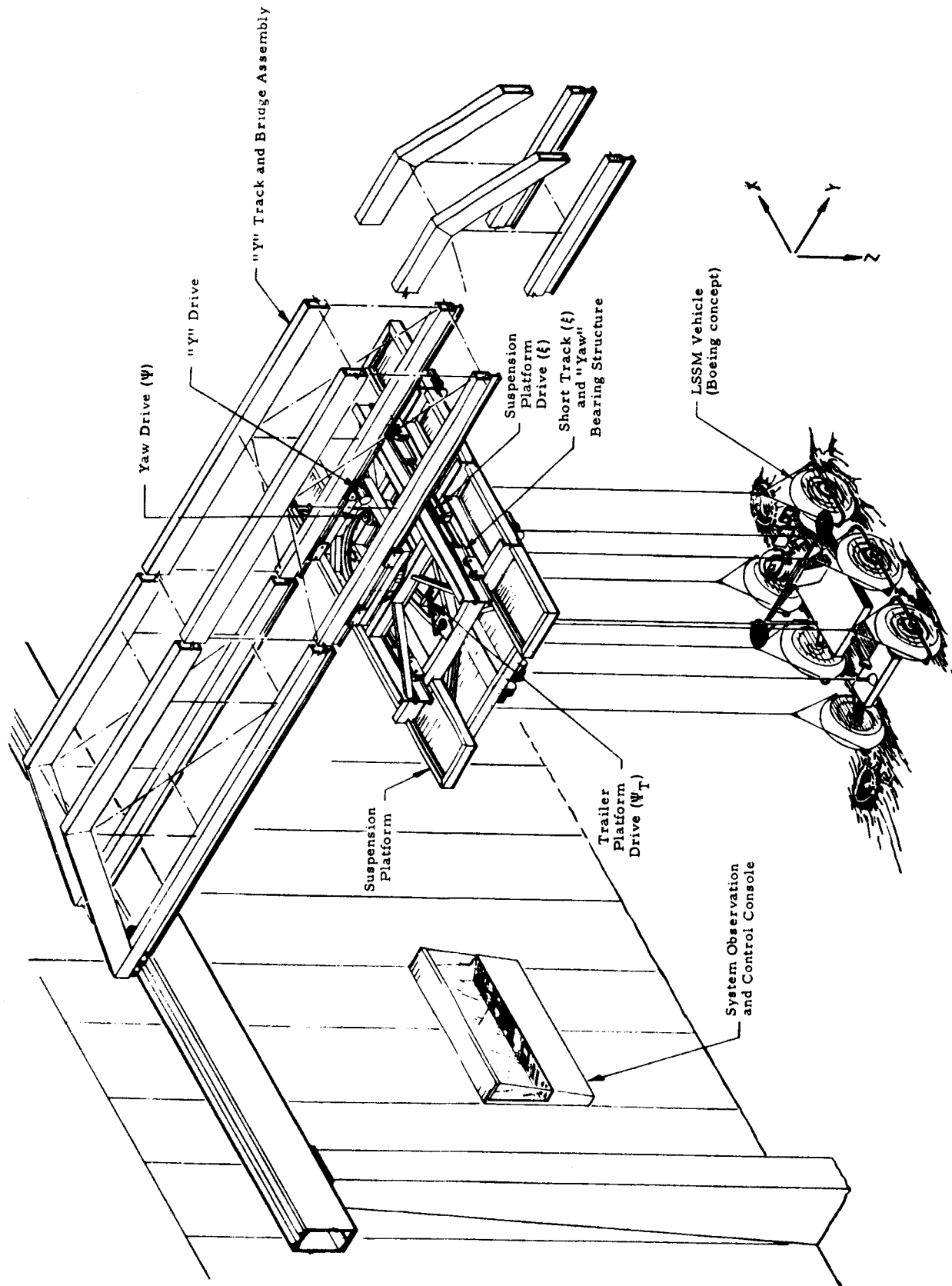


Figure 1 - Lunar Gravity Simulator for Lunar Surface Vehicles

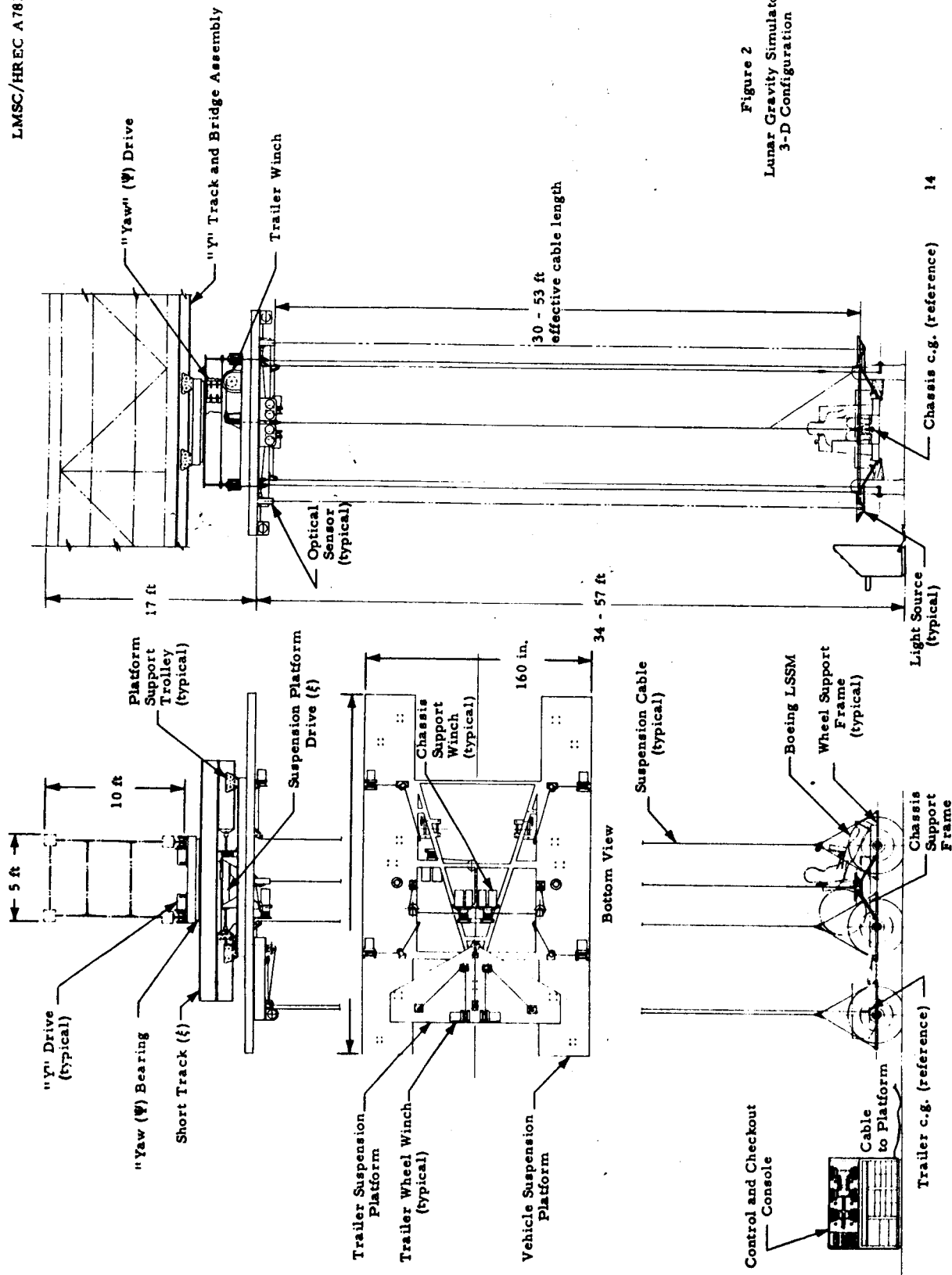


Figure 2
Lunar Gravity Simulator
3-D Configuration

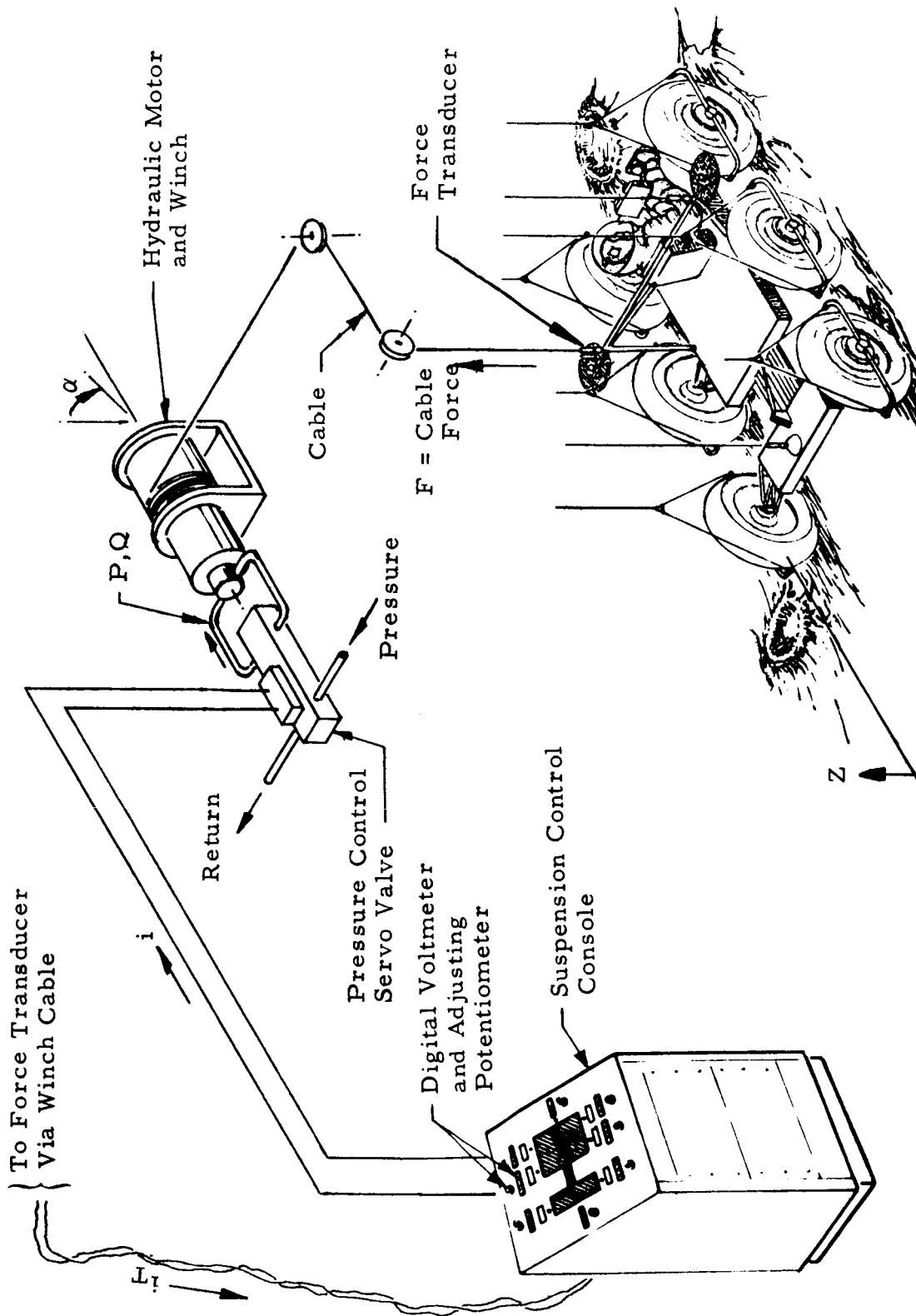


Figure 3 - Typical Constant Force Control System

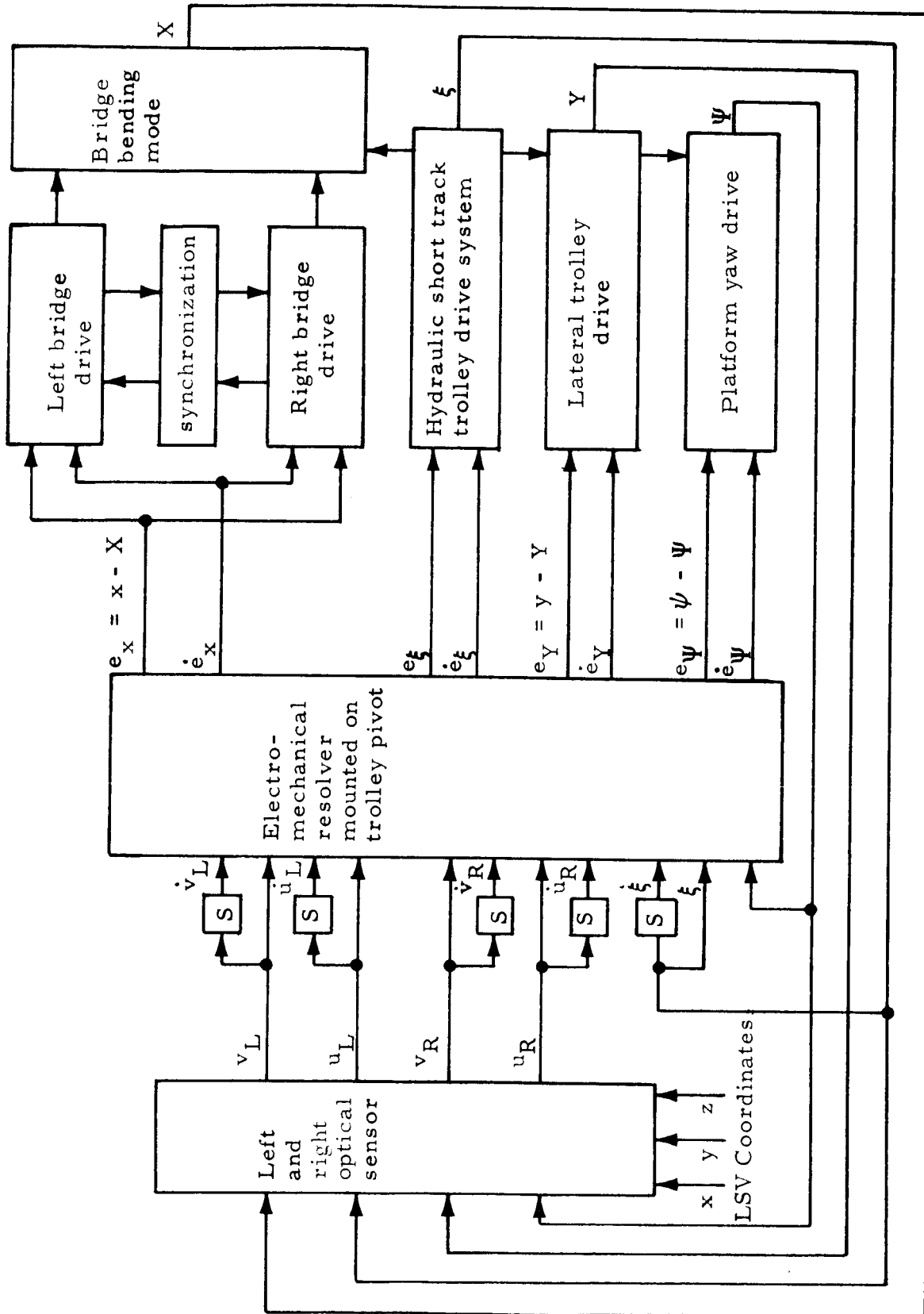


Figure 4 - Overall Block Diagram for Trolley Positioning Control Using Two Optical Sensors

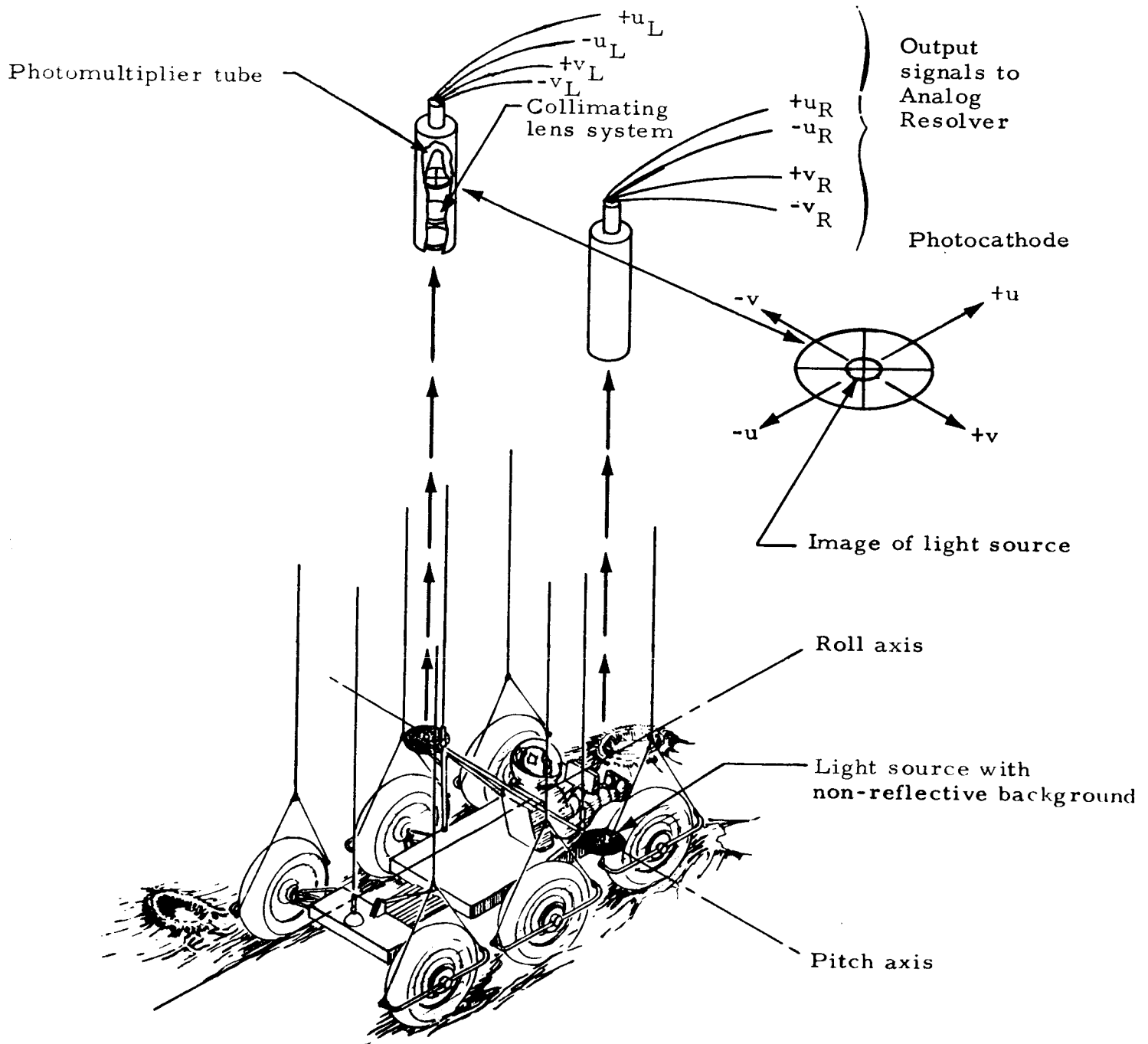


Figure 5 - Optical Tracking System

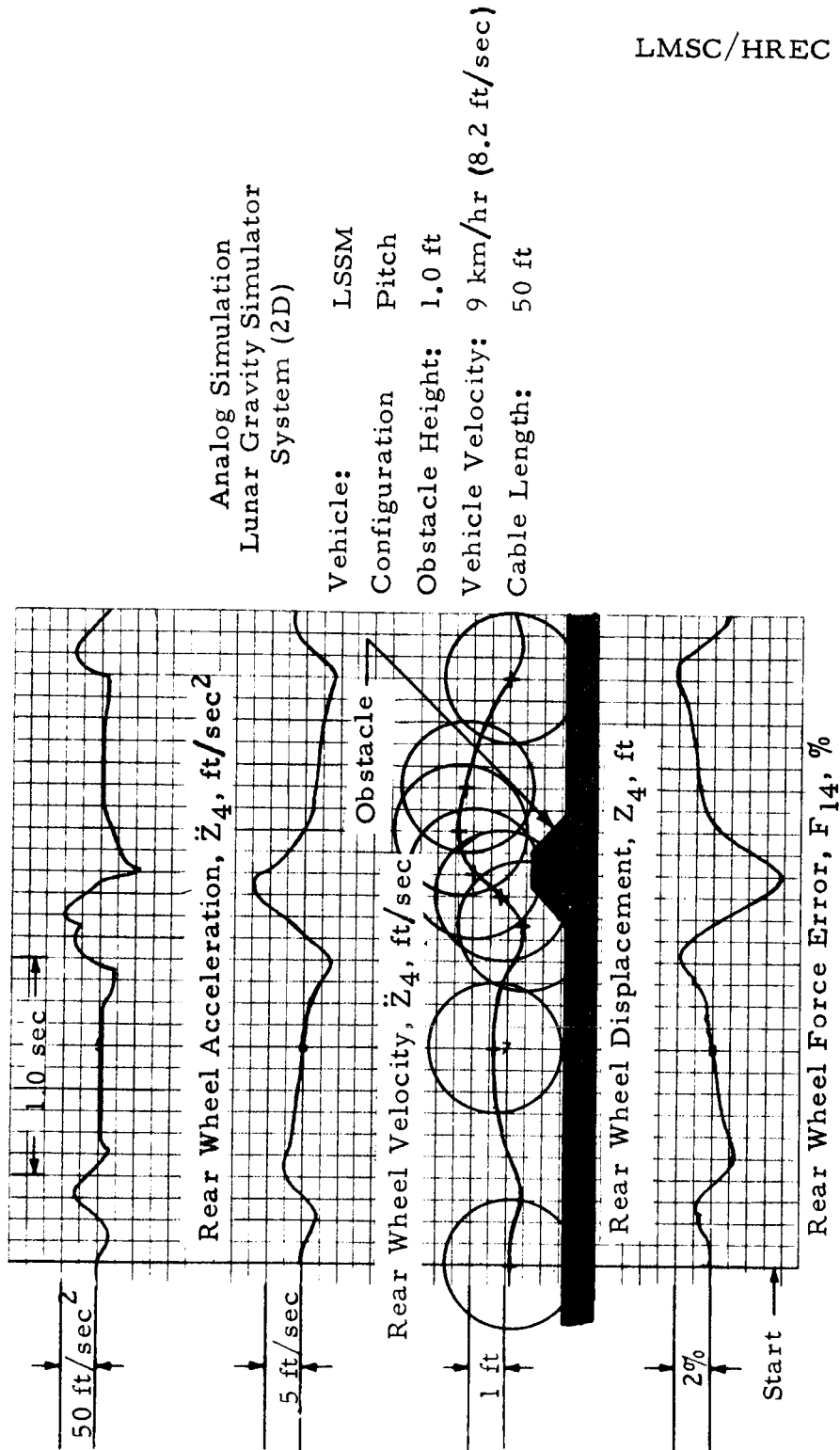


Figure 6 - Force Control System Performance with LSSM Front and Rear Wheels Engaging Obstacle (Pitch Configuration)

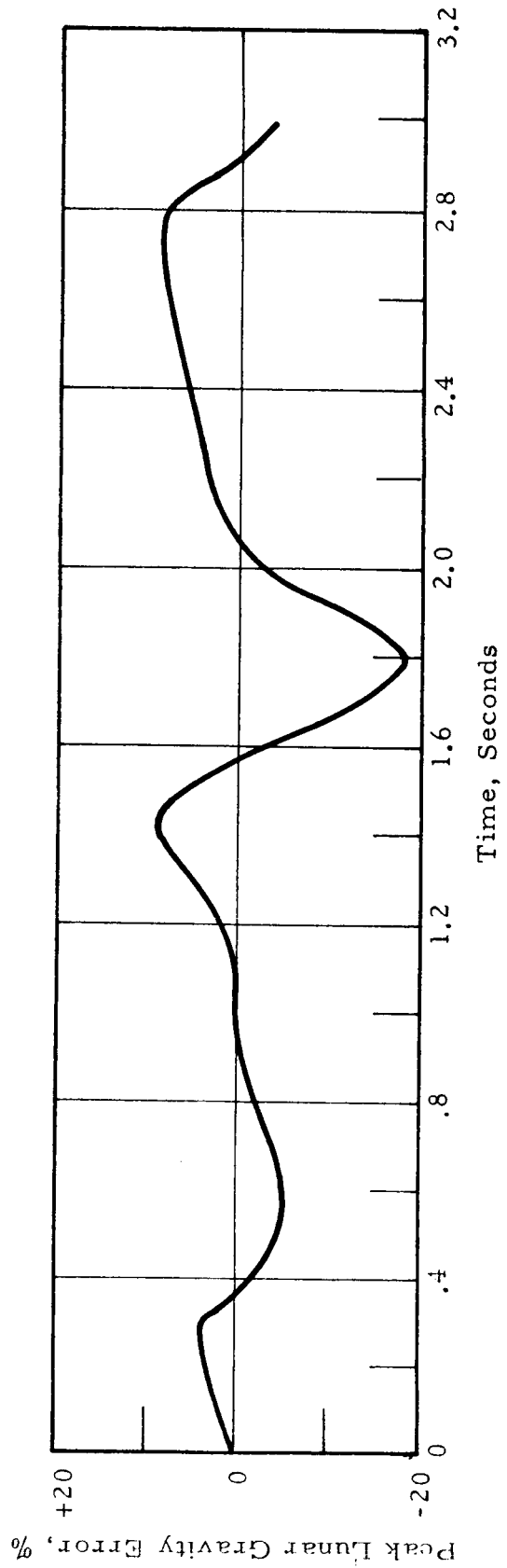
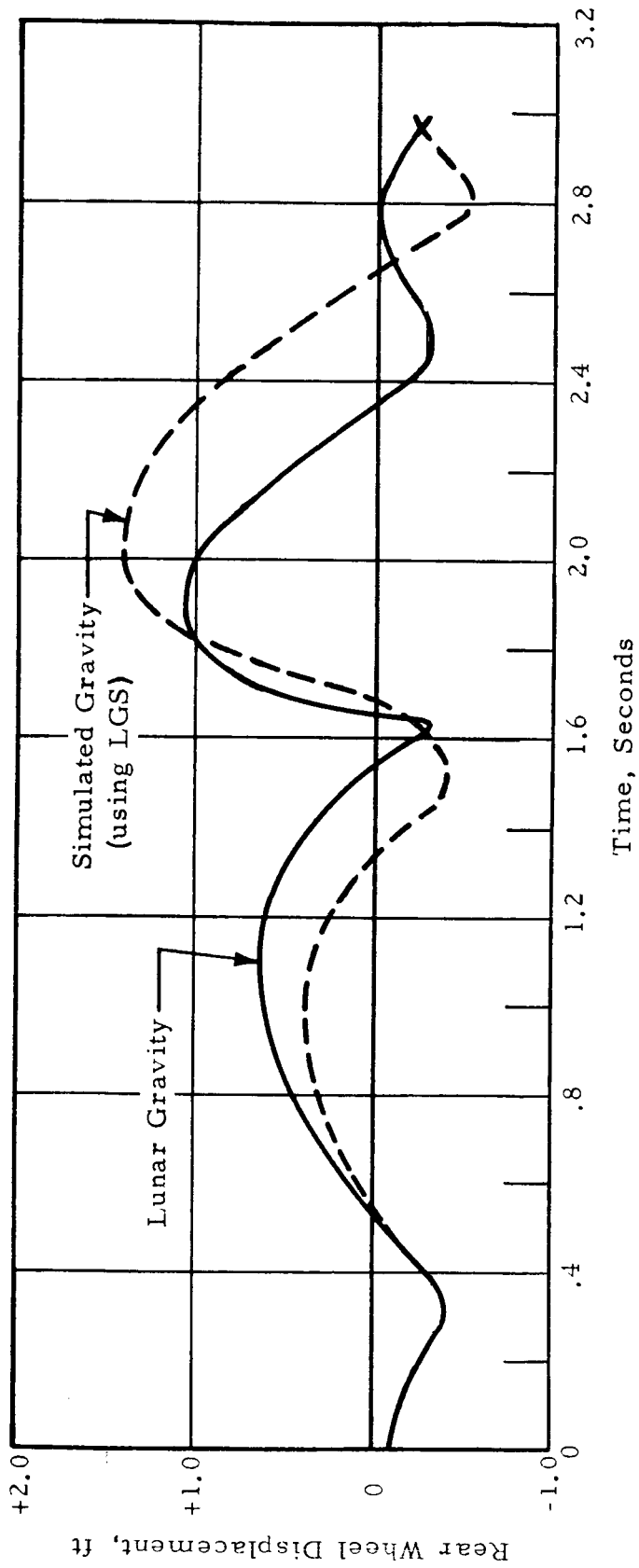


Figure 7 - LSSM Rear Wheel Displacement and Peak Lunar Gravity Error

$\dot{X} = 9.0 \text{ km/hr (8.2 ft/sec)}$ Obstacle Height = 1.0 ft

Cable Length = 50 ft

Pitch Configuration

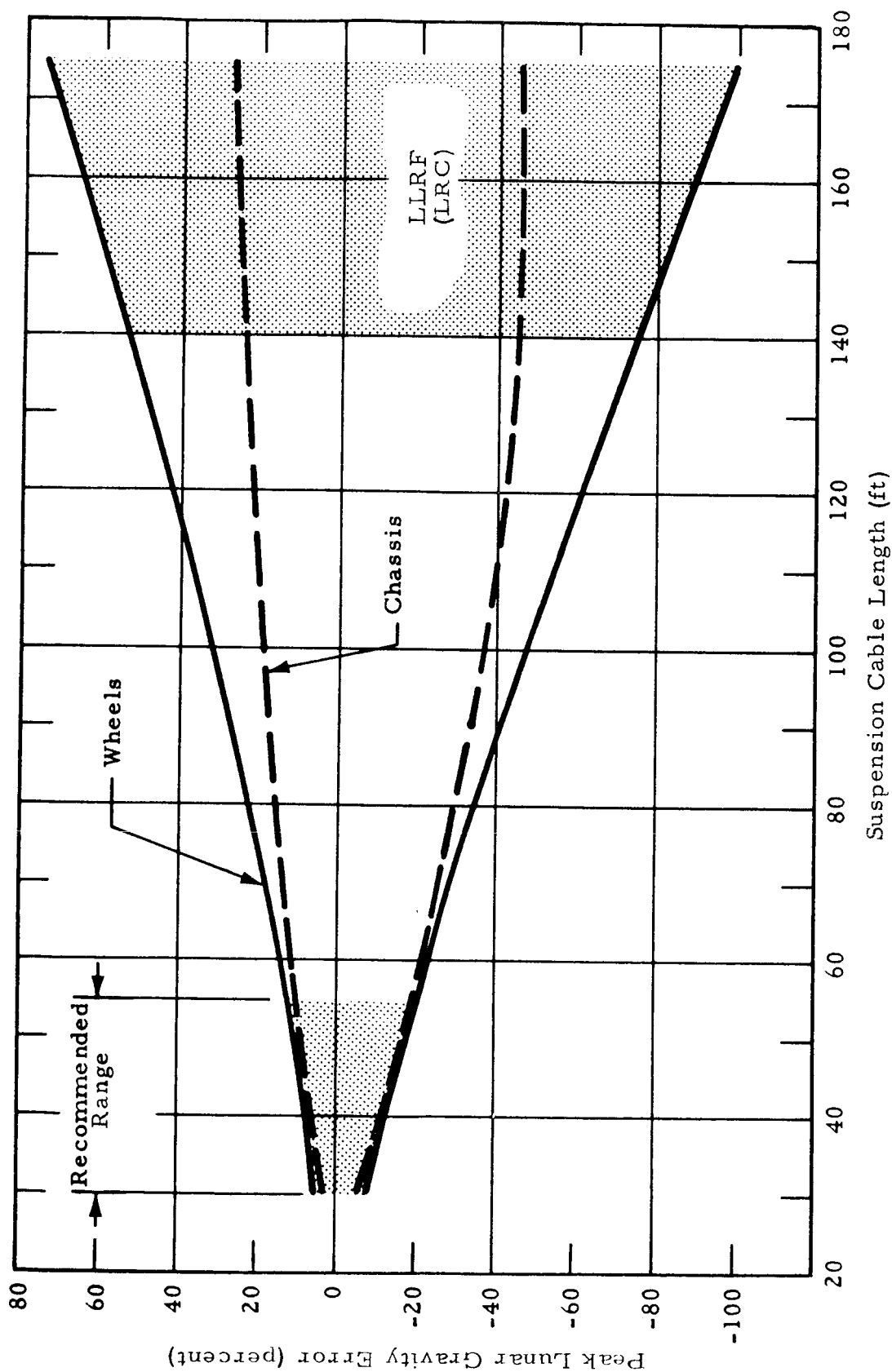


Figure 8 - Lunar Gravity Peak Error vs Cable Length for LSSM in Pitch Configuration

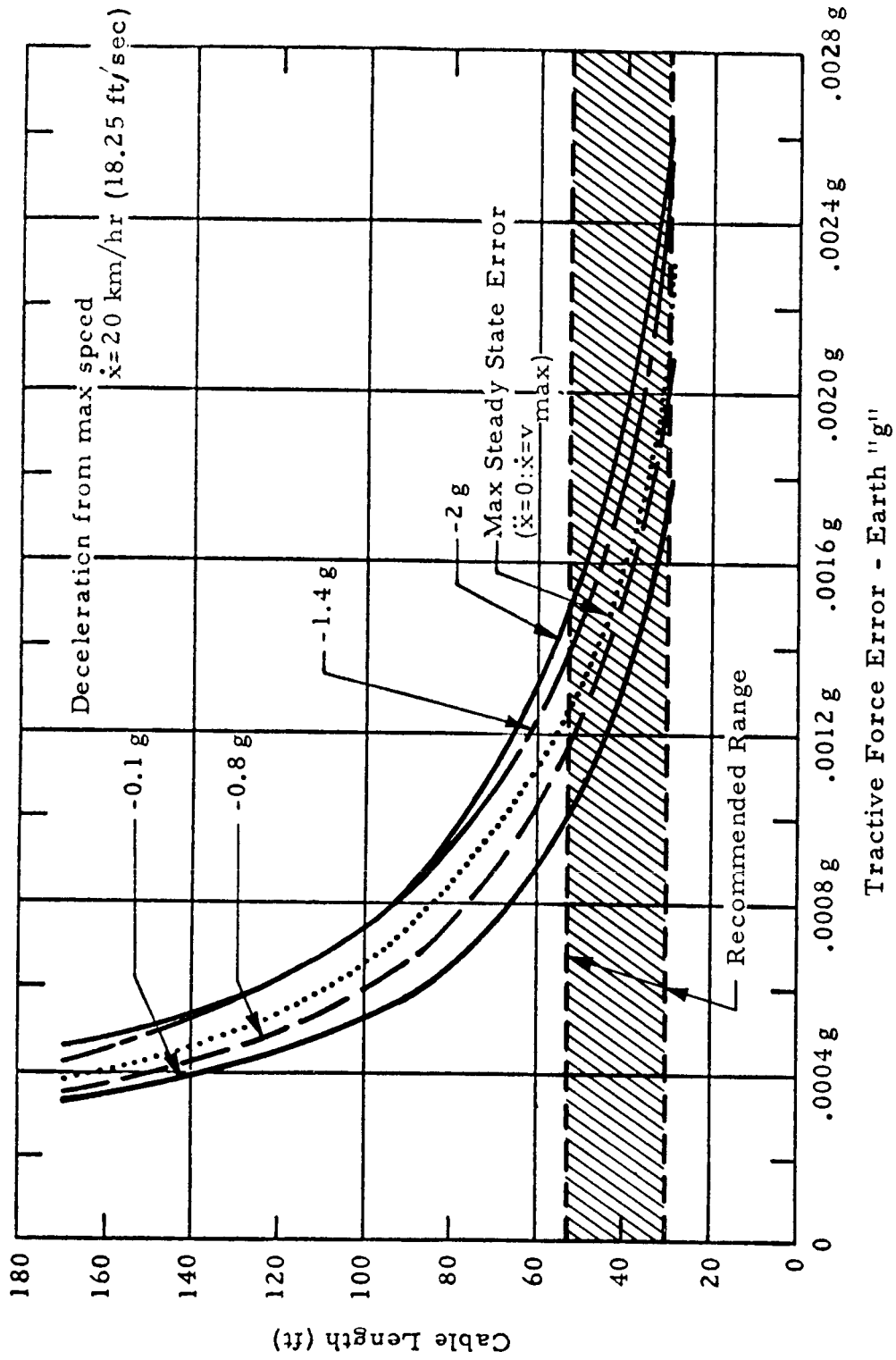


Figure 9 - Effect of Cable Length on the LSV Tractive Force Error for Various Decelerations (X) MOLAB Vehicle $\dot{x} = 20$ km/hr (18.25 ft/sec)

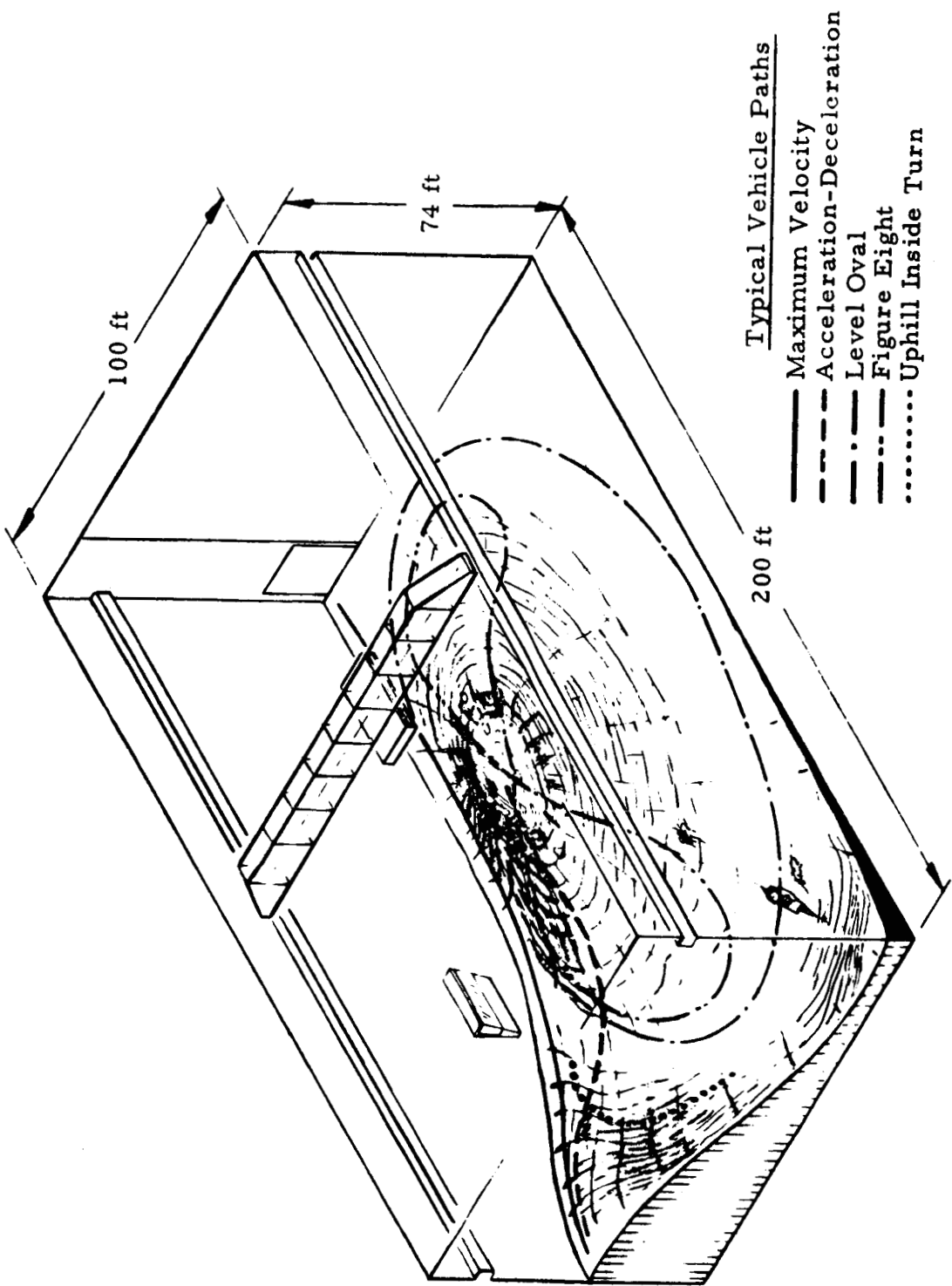


Figure 10 - 3-D LGS with Simulated Lunar Terrain Configuration